

# AN EXPERIMENTAL INVESTIGATION OF THE SEPARATING/REATTACHING FLOW OVER A BACKSTEP

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Transport characteristics of the turbulent kinetic energy,  $k$ , and the shear stress,  $-\overline{uv}$ , were studied in an incompressible boundary layer downstream of the reattachment of the separated flow behind a backward-facing step. Hot-wire measurement technique was used to measure three Reynolds stresses and higher-order mean products of velocity fluctuations. These quantities were used to evaluate advection, turbulent diffusion, and production terms of the  $k$  and  $-\overline{uv}$  transport equations. The dissipation rate and pressure-strain terms were obtained as the difference of all the other terms.

The turbulent structure downstream of the reattachment deviates from the state of equilibrium of a zero-pressure gradient boundary layer (regular boundary layer). All terms of transport equations are of the same magnitude downstream of the mean reattachment point up to about  $30h$  when the turbulence structure begins to resemble standard turbulent boundary layer structure. It appears that advection and production terms are negligibly small in the wall proximity,  $y/\delta < 0.2$ , for  $x < 10h$  so that the dissipation and diffusion terms are in balance. In the outer part of the flow, however, the decay process is much slower so that the flow retains a memory of the upstream disturbance even at the last measuring station of 51 step-heights. Prandtl mixing length,  $l/\delta$ , and eddy-viscosity,  $\nu_t/(U_e\delta^*)$ , were obtained directly from the measured shear stress and mean streamwise velocity. Variation of the mixing length is linear in the wall region, however, the slope is at least two times that of a regular boundary layer sufficiently close to the mean reattachment location. Far downstream, the slope near the wall approaches the standard value of 0.41. In the outer flow region, the mixing length becomes almost constant far downstream but retains high values which are about two times that of the regular boundary layer. Eddy viscosity distribution behaves similarly. It changes linearly with a larger slope in the wall region than that of a regular boundary layer and attains values in the outer region which are as high as four times that of a regular boundary layer.

The Reynolds number based on the step height was 37000 and the upstream oncoming flow was fully developed turbulent boundary layer with the  $R_\theta = 3600$ .

## INTRODUCTION

Separated/reattached flows occur in wide variety of practical engineering applications and therefore has attracted attention of many researchers. This flow deviates from a self-similar equilibrium flow structure. The fully developed turbulent structure of the upstream boundary layer is perturbed by a discontinuity in the boundary condition. A non-slip and impervious wall abruptly ends at the step lip allowing the internal mixing layer, inbedded in the turbulent boundary layer, to develop further downstream. The structure of the separated shear layer strongly resembles that of a plane-mixing layer as it evolves downstream. However, there is a new change of the boundary condition representing a new perturbation of the flow. The mixing-layer like structure encounters a solid and impervious wall in the reattachment region when it has to change its character and transform to that characteristic of a regular boundary layer. The response of the turbulent structure is not instantaneous across the entire flow as the perturbation is imposed on the flow. It is rather slow and gradual. In the recovery region, downstream of the reattachment, it appears that rates of recovery in the two parts of the flow, near-wall and outer flow regions, are quite different ( Jovic & Browne). The turbulent structure near the wall recovers much faster to

that of a regular boundary layer than the one in the outer part of the flow. Fundamental complexities of the turbulent structure of this family of turbulent flows presents a real challenge for the available turbulence models.

Numerous studies have been conducted on separated/reattached flows during the past four decades. The research has been conducted for different geometric configurations, however, fundamental features of this class of flows have been addressed most frequently for a backward-facing step induced separation.

Extensive studies on separated flow for a blunt plate are made by Cherry, Hiller & Latour (1984) and Kiya & Sasaki (1983,1985). Ruderich & Fernholz (1986), Castro & Hague (1987) and Cutler & Johnston (1989) studied structure of a separated flow behind a normal plate ( fence) with a splitter plate. Chandrsuda & Bradshaw (1981), Kim et al.(1978), Westphal (1983), Eaton & Johnston (1982), Pronchick & Kline (1983), Driver & Seegmiller (1983), Adams & Johnston (1988), just to name a few, conducted extensive measurements of a separated flow behind a backward-facing step.

The objective of the present experiment is to present a detailed analysis of an evolution of the transport mechanisms of the turbulent kinetic energy,  $k$ , and the shear stress,  $-\overline{uv}$ , in the recovery region of the attached boundary layer downstream of the reattachment point. Important implications are presented pertaining to turbulent models.

## 2. APPARATUS, TECHNIQUES AND CONDITIONS

The measurements were performed in a wind tunnel comprised of a symmetric three-dimensional 9:1 contraction, a 169cm long flow development section with dimensions 19.7cm x 42cm, a backward-facing step of the height,  $h$ , of 3.8cm and a 205cm long recovery section. The flow was tripped at the inlet of the development section using 1.6mm diameter wire followed by a 110mm width of 40 grit emery paper. The side walls diverged slightly outwards to assure approximate zero-pressure gradient in the development and the recovery sections of the tunnel. All the measurements were made at a flow speed,  $U_{ref}$ , of 14.7m/s measured at a station 40mm upstream of the step. A free stream turbulence intensity was 0.4%. The boundary layer was fully turbulent at a reference station having a Reynolds number based on a momentum thickness,  $R_\theta$ , of 3600 and a shape factor,  $H$ , of 1.4. A boundary layer thickness,  $\delta \equiv \delta_{99}$ , was 31mm resulting with  $\delta/h = 0.8$ . This perturbation can be classified as a strong perturbation ( Bradshaw & Wong (1972)). The aspect ratio ( tunnel width/step height) of 11 is just above the value of 10 recommended by de Brederode & Bradshaw (1972) as the minimum to assure two-dimensionality of the flow in a central region of a tunnel. An expansion ratio was 1.19 and the Reynolds number based on the step height was 37000.

Mean velocity and turbulence measurements were made with normal and X-wire probes driven by an in-house built constant-temperature anemometers. The sensor filaments were made of 10% Rhodium-Platinum wire  $2.5\mu m$  in diameter and  $0.6mm$  ( or 22 in wall units in the upstream boundary layer) in length for the X-wire probe, and  $1.25\mu m$  in diameter and  $0.3mm$  ( or 11 wall units) in length for the normal-wire probe. The spacing between crossed wires was  $0.4mm$  or 15 wall units. The aspect ratio,  $l/d$ , of the sensor filaments was 240 for both probes. The geometry of the sensor filaments were

very well suited for the near wall measurements due to the inherent problems with the spatial resolution very close to the wall. The usual  $90^\circ$  included angle of the crossed wires was replaced by the  $110^\circ$  angle. This angle is chosen to improve accuracy of the measurements in the regions with higher levels of local turbulence intensity. Constant temperature anemometers were operated at overheat ratios of 1.3 with a frequency response of  $25kHz$  as determined by the square wave test. The normal-wire signal was low-pass filtered at  $10kHz$  and was digitized at 20 ksamples/sec for 30 sec. The X-wire signals were low-pass filtered at  $6kHz$  and were sampled at 12 k samples/sec for 30 sec. Analog signals were digitized using Tustin A/D converter with the 15 bit ( plus sign) resolution. The probes were calibrated using a static calibration procedure and calibration data of each hot-wire channel were fitted with a fourth order polynomial.

### 3. RESULTS

#### 3.2 Transport of the turbulent kinetic energy

A low viscosity oil was used to visualize the flow pattern in the separated region and to determine the mean reattachment length. The reattachment line is not a straight line in the spanwise direction but curves upstream near the side walls. Flow reattachment occurs at about  $x/h = 6.84$  in the mid plain of the wind tunnel. Regardless of the fact that the oil-flow picture represents only a mean footprint of the flow it reveals a three-dimensional nature and a specific pattern of the interaction of the flow with the wall in the reattachment region. Eaton & Johnston (1982) and Westphal, Johnston & Eaton (1984) quantified the observed unsteadiness in the reattachment region using thermal-tuft probe. Two modes of unsteadiness were observed in the separated flow of a blunt plate ( Cherry, Hiller & Latour (1984), Kiya & Sasaki (1983,1985)) and normal plate with a splitter plate (Castro & Haque (1987)). Similar observations were made for backward- facing step separation by Eaton & Johnston (1982), Adams, Johnston & Eaton (1984) and Driver & Seegmiller (1983).

The balance of the turbulence kinetic energy in three streamwise loactions (  $9.87h$ ,  $20.29h$  and  $38.55h$ ) is shown in Figure 1. The turbulent kinetic energy equation for two-dimensional flows may be written as follows:

$$U \frac{\partial k}{\partial x} + V \frac{\partial k}{\partial y} = - \frac{\partial}{\partial x} \overline{u \left( k + \frac{p}{\rho} \right)} - \frac{\partial}{\partial y} \overline{v \left( k + \frac{p}{\rho} \right)} - (\overline{u^2} - \overline{v^2}) \frac{\partial U}{\partial x} - \overline{uv} \frac{\partial U}{\partial y} - \epsilon$$

All terms of the transport equation were evaluated from the measured turbulent quantities except the rate of dissipation, which was obtained by difference. The turbulent kinetic energy,  $k$ , was approximated by  $\frac{3}{4}(\overline{u^2} + \overline{v^2})$ , turbulent diffusion in the streamwise direction,  $\overline{uk}$ , and in the transverse direction,  $\overline{vk}$ , were approximated by  $\frac{3}{4}(\overline{u^3} + \overline{u^2v})$  and  $\frac{3}{4}(\overline{u^2v} + \overline{v^3})$  respectively. Contribution by fluctuating pressure-velocity covariances to the turbulent

transport is typically small in wall bounded flows and was therefore neglected. However, this approximation may be quite crude in the reattachment region of separated flows where large pressure and velocity fluctuations take place.

Downstream of the reattachment flow accelerates and undergoes structural adjustments to the new boundary condition. The diffusion peak in the outer part of the flow occurs approximately at  $0.4\delta$ . It appears that the peaks of the turbulent diffusion and production do not coincide. The peak of the diffusion represents a significant ratio of the production peak and is about 0.85. This ratio is sustained up to about  $30h$  downstream from the step or about three mean reattachment lengths. In a regular equilibrium turbulent boundary layer, contributions by convection, longitudinal diffusion and production by the normal stresses are negligibly small. However, it was found that a contribution of the three terms, longitudinal turbulent diffusion,  $\partial(\overline{uk})/\partial x$ , production by the normal stresses,  $-(\overline{u^2} - \overline{v^2})\partial U/\partial x$ , and the mean flow transport are significant downstream of reattachment (not presented here).

The production peak occurs at about  $0.5\delta$  in the transverse direction and dominates the wall production up to about  $15h$  or one reattachment length downstream from the mean reattachment point. Downstream of this location, production in the wall region rapidly increases indicating the growth of an internal turbulent boundary layer. Familiar wall mechanisms dominate wall turbulence production, while the excess of the turbulent energy in the outer part of the flow diminishes almost entirely so that the production profile resembles that of the regular boundary layer by the streamwise distance of about  $30h$ . This is consistent with the findings of Jovic & Browne (1990) which were based on the stress measurements.

Due to the very important role of the turbulent diffusion in the transport of the kinetic energy in the recovery region any correct prediction of the separated/reattached flow implies accurate modelling of the diffusion terms.

It appears that the loss of turbulent energy by dissipation in the inner part of the flow,  $y < 0.2\delta$ , is balanced by diffusion due to negligibly small contributions of turbulent energy by production and convection. This is true up to about one reattachment length downstream from the mean reattachment point. This implies that turbulence models which apply equilibrium concepts are not applicable in this region.

In the outer part of the flow,  $y > 0.8\delta$ , the loss of the turbulent kinetic energy by convection and dissipation are balanced by a large magnitude of diffusion.

### 3.2 Transport of the shear stress

The balance of the turbulence kinetic energy in three streamwise locations ( $9.37h$ ,  $20.29h$  and  $38.55h$ ) is shown in Figure 2. The turbulent kinetic energy equation for two-dimensional flows may be written as follows:

$$U \frac{\partial(-\overline{uv})}{\partial x} + V \frac{\partial(-\overline{uv})}{\partial y} = -\frac{\partial}{\partial x} \left( \frac{\overline{p}}{\rho} v - \overline{u^2 v} \right) - \frac{\partial}{\partial y} \left( \frac{\overline{p}}{\rho} u - \overline{uv^2} \right) + \overline{v^2} \frac{\partial U}{\partial y} + \overline{u^2} \frac{\partial V}{\partial x} - \frac{\overline{p}}{\rho} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)$$

The turbulent diffusion done by pressure,  $\overline{vp/\rho}$  and  $\overline{up/\rho}$ , and the production term by the normal stress  $\overline{u^2}(\partial V/\partial x)$  were neglected. Advection term is smaller than in the case of the turbulence kinetic energy transport shown Figure 1. Three terms which dominate transport mechanism are production,  $\overline{v^2}(\partial U/\partial y)$ , combined longitudinal and transverse turbulent diffusion and the pressure-strain term. In the central portion of the flow, maxima of the shear stress production occur at the same location as the production of the turbulent energy. This gain of the shear stress by the production is balanced by the large turbulent diffusion term and the pressure-strain term. The gain by diffusion and the loss by the pressure-strain term are not balanced in the near-wall region. The production term is of the same magnitude and sign as the diffusion term in the near wall region. The production of the shear stress has significantly increased near the wall by  $x = 20h$ . Distributions of diffusion and pressure-strain terms in the wall region resemble the regular boundary layer by  $30h$ . At this location, all three terms are still large in the outer flow region. It appears that the pressure-strain and production balance by the streamwise location of  $38h$ . Profiles of different terms of the shear stress transport equation are roughly the same shape as in a boundary layer by the last measuring station.

### 3.3 Derived quantities and their implications on modelling

Stream line curvature was neglected in the recovery region so that the shear stress and mean streamwise velocity, which were measured in the Cartesian coordinate system, were used to evaluate the Prandtl's mixing length and eddy viscosity. Mixing-length,  $l = \sqrt{-\overline{uv}}/(\partial U/\partial y)$ , and eddy-viscosity,  $\nu_t = -\overline{uv}/(\partial U/\partial y)$ , are two turbulence models which have been successfully used in calculating slow evolving self-preserving flows. However, these simple models fail in more complex flow configurations where the Reynolds stresses respond slowly to the rapid changes of the rate of strain.

Non-dimensional mixing-length,  $l/\delta$ , and eddy-viscosity,  $\nu_t/U_e\delta^*$ , are shown in Figure 3. and Figure 4. respectively. Distribution of the respective quantities are compared with the ones of the upstream fully developed boundary layer. Note that the Reynolds number of the upstream boundary layer of  $R_\theta = 3600$  is lower than the one in the recovery region of the flow. Values of the Reynolds number for the given  $R_h$  are typically over 9000 in the recovery region.

Near the wall the mixing length is a linear function of the normal distance from the wall. However, the slope is much larger than the value of 0.41 typical of an equilibrium boundary layer. Moreover, the distribution in the outer part of the flow deviates from the constant value exceeding the value of 0.08 characteristic of an equilibrium boundary layer. In the downstream stations the mixing length approaches the standard distribution near the wall while it attains a quasi-constant value of about 0.19 in the outer region for  $x > 30h$ . It appears that the turbulent structure reaches a quasi-equilibrium state in the outer part of the flow which evolves very slowly further downstream. This observation is consistent with that made for the transport equation of the turbulent kinetic energy.

Similarly, the eddy-viscosity,  $\nu_t/U_e\delta^*$ , deviates both in the wall and the outer flow regions from the distribution of the upstream boundary layer. Non-dimensional eddy-viscosity rises initially reaching the value of 0.075 in  $x = 20h$  when it subsequently begins

to decay at a very slow rate. Even at the last measuring station,  $x = 51h$ , non-dimensional value of the eddy-viscosity is about four times greater than the value of an equilibrium boundary layer of 0.017. These high values of the mixing length in the outer parts of the flow far downstream indicate presence of structures of larger scales which carry the memory of the perturbation of the flow. High values of eddy viscosity consequently indicate intensive turbulent mixing when compared to a regular boundary layer.

#### 4. Conclusions

The results presented and discussed in the previous sections led to the following conclusions about the recovering turbulent structure of the flow downstream of the reattachment point. The thin-shear layer approximation is inapplicable in the recovery region of a separated flow. Longitudinal turbulent diffusion and production of the turbulent energy by the normal stresses play an important role in the transport balance of the turbulent kinetic energy transport equation. Turbulent diffusion and dissipation are balanced in the near-wall part of the flow for some distance downstream of the mean reattachment point. Production in the wall region dominates production across the recovering boundary layer by the downstream distance of  $30h$  or about three mean reattachment lengths downstream of the reattachment point. Mixing length and eddy viscosity exceed the values of a regular boundary layer several times even at the last measuring station.

#### ACKNOWLEDGMENTS

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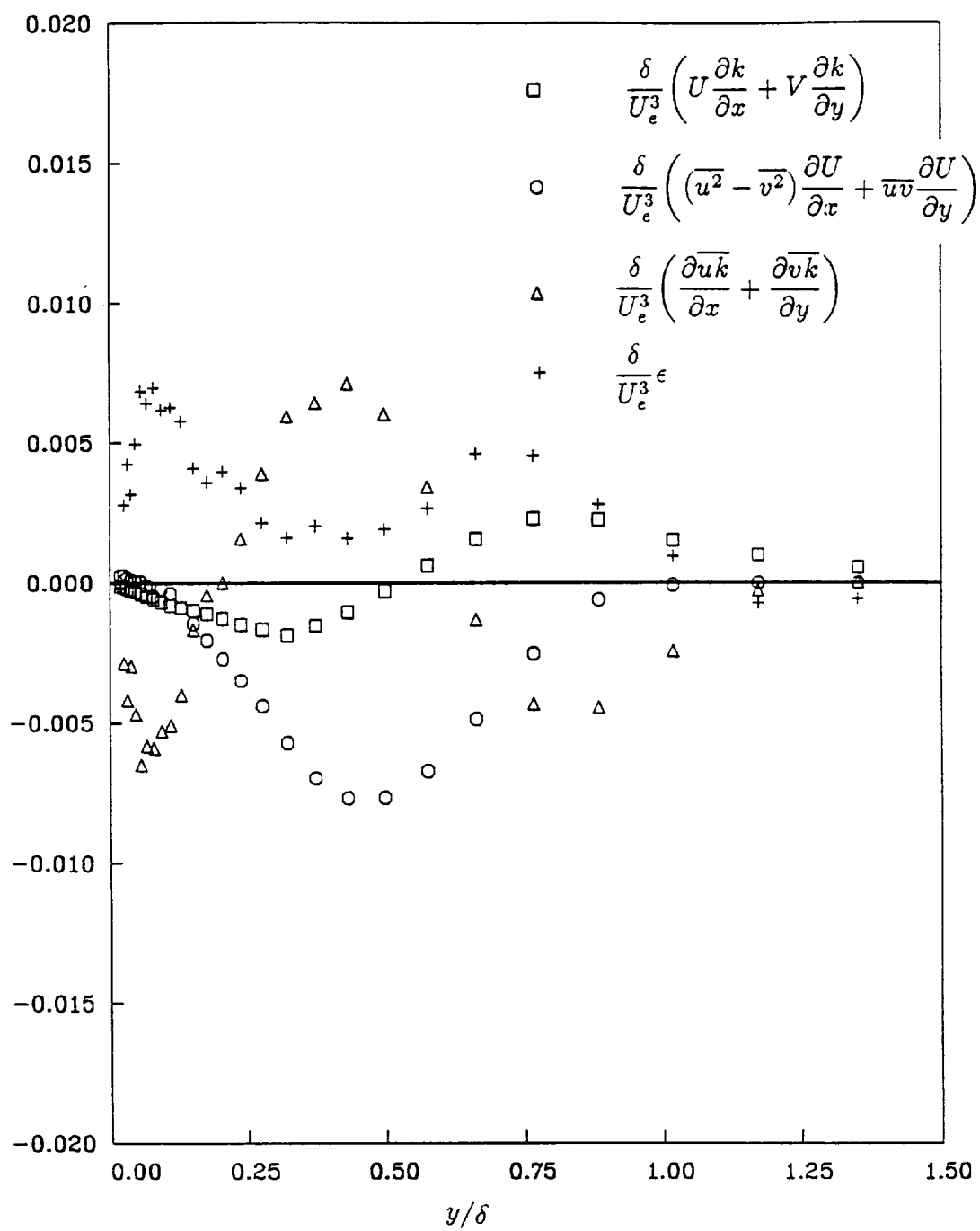
### Figure Captions

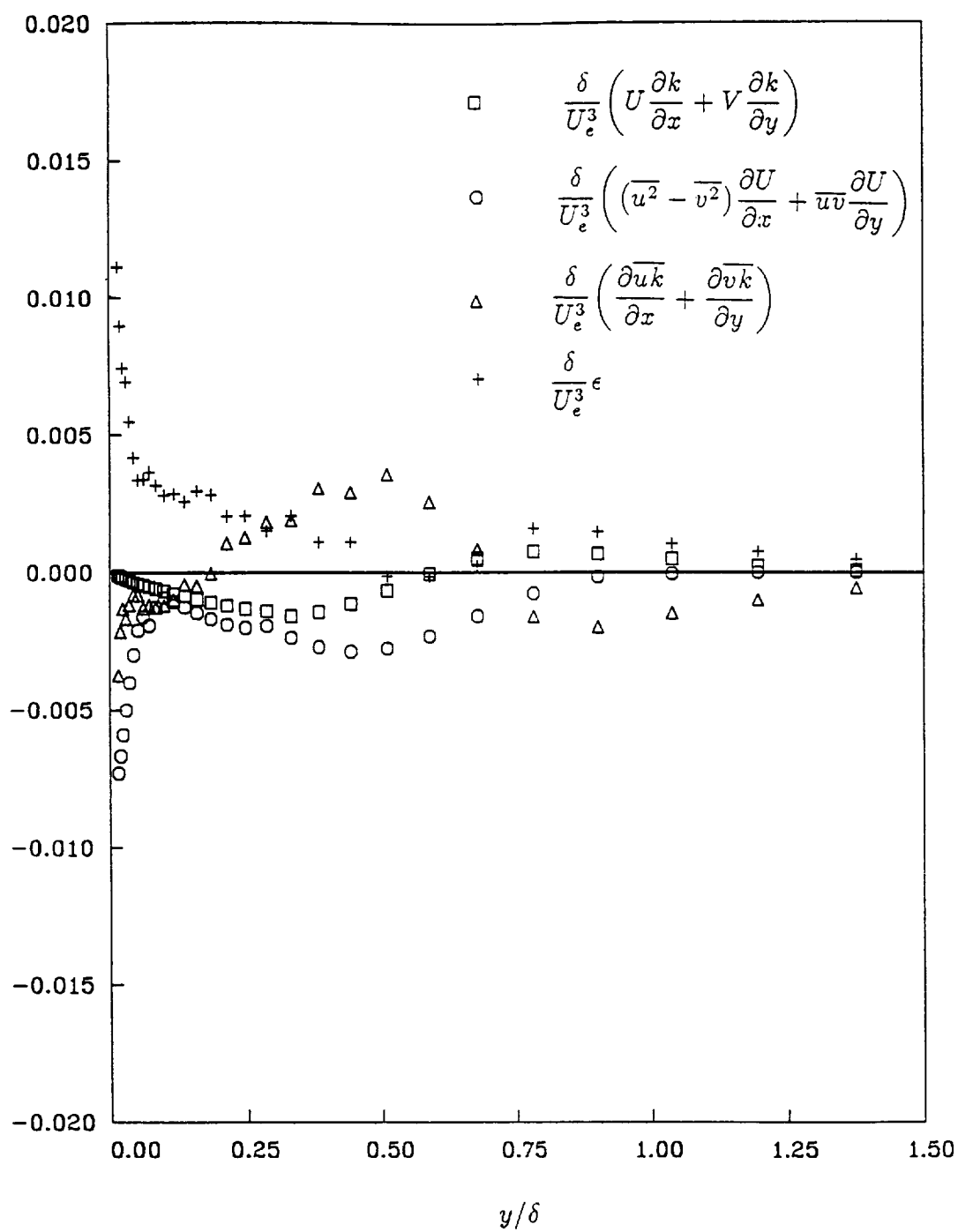
**Figure 1.** Profiles of terms in the turbulent kinetic energy equation a)  $x = 9.87h$ , b)  $20.3h$ , c)  $38.6$

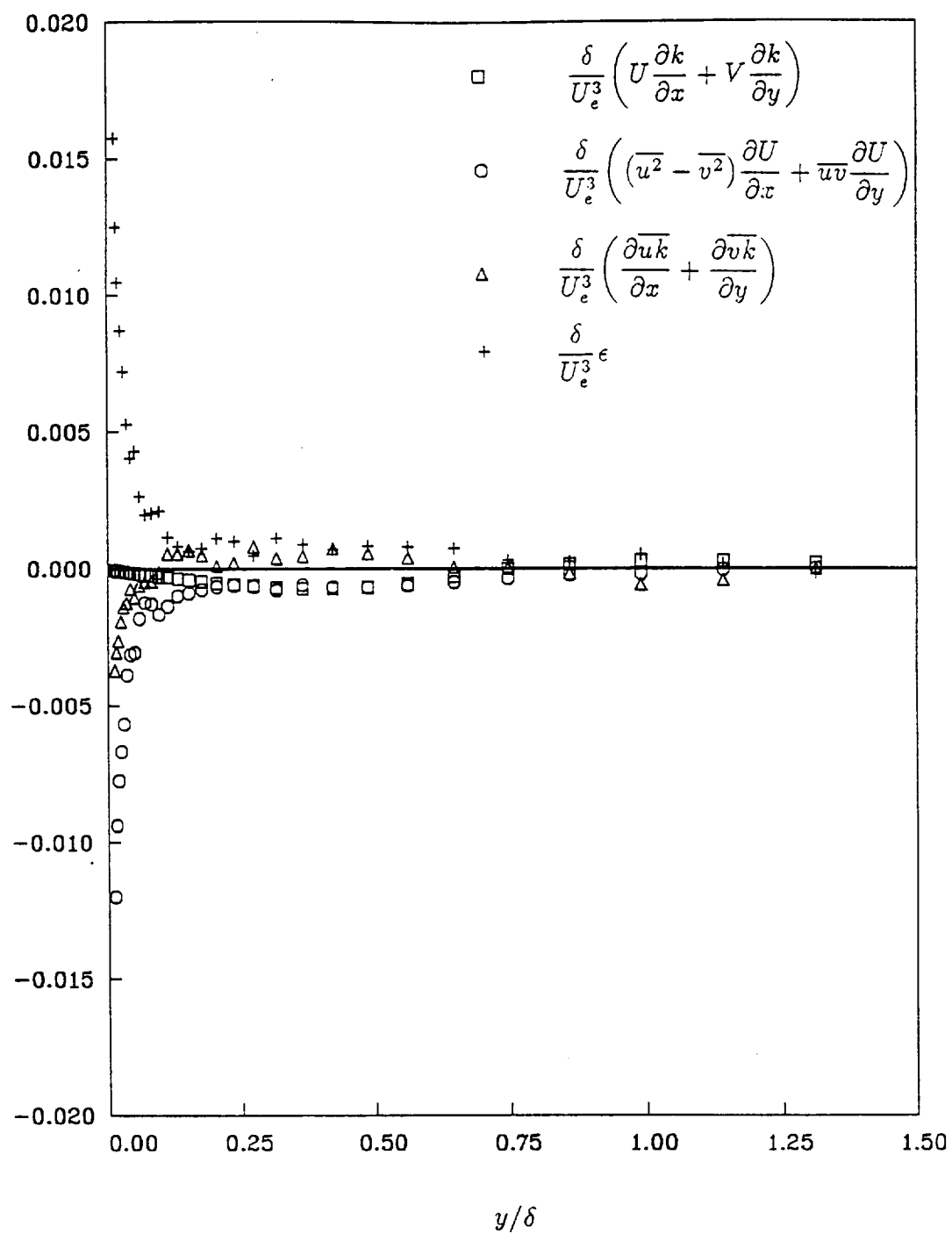
**Figure 2.** Profiles of terms in the shear stress transport equation a)  $x = 9.87h$ , b)  $20.3h$ , c)  $38.6$

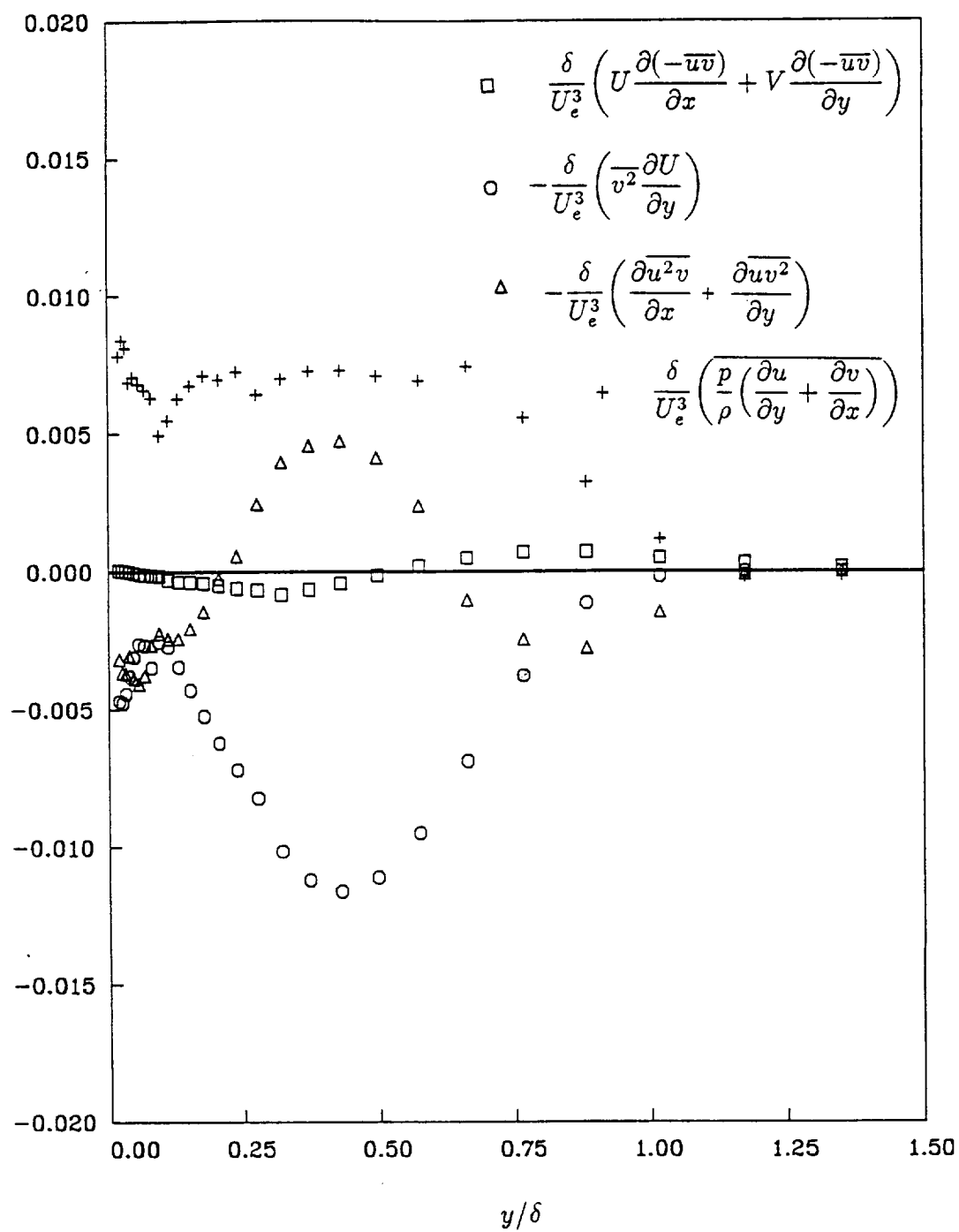
**Figure 3.** Profiles of the mixing length for the indicated measuring stations.

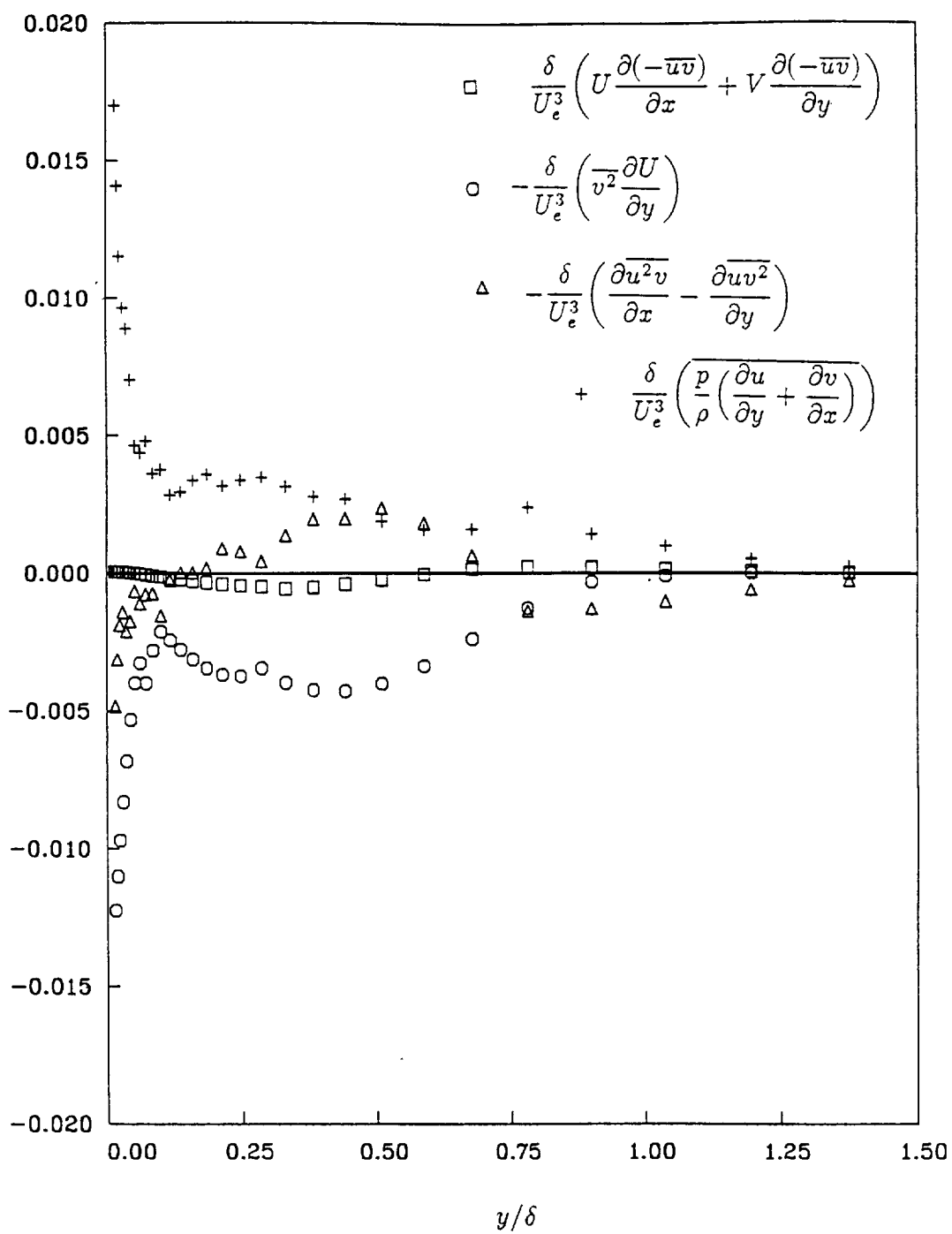
**Figure 4.** Profiles of the eddy viscosity for the indicated measuring stations.

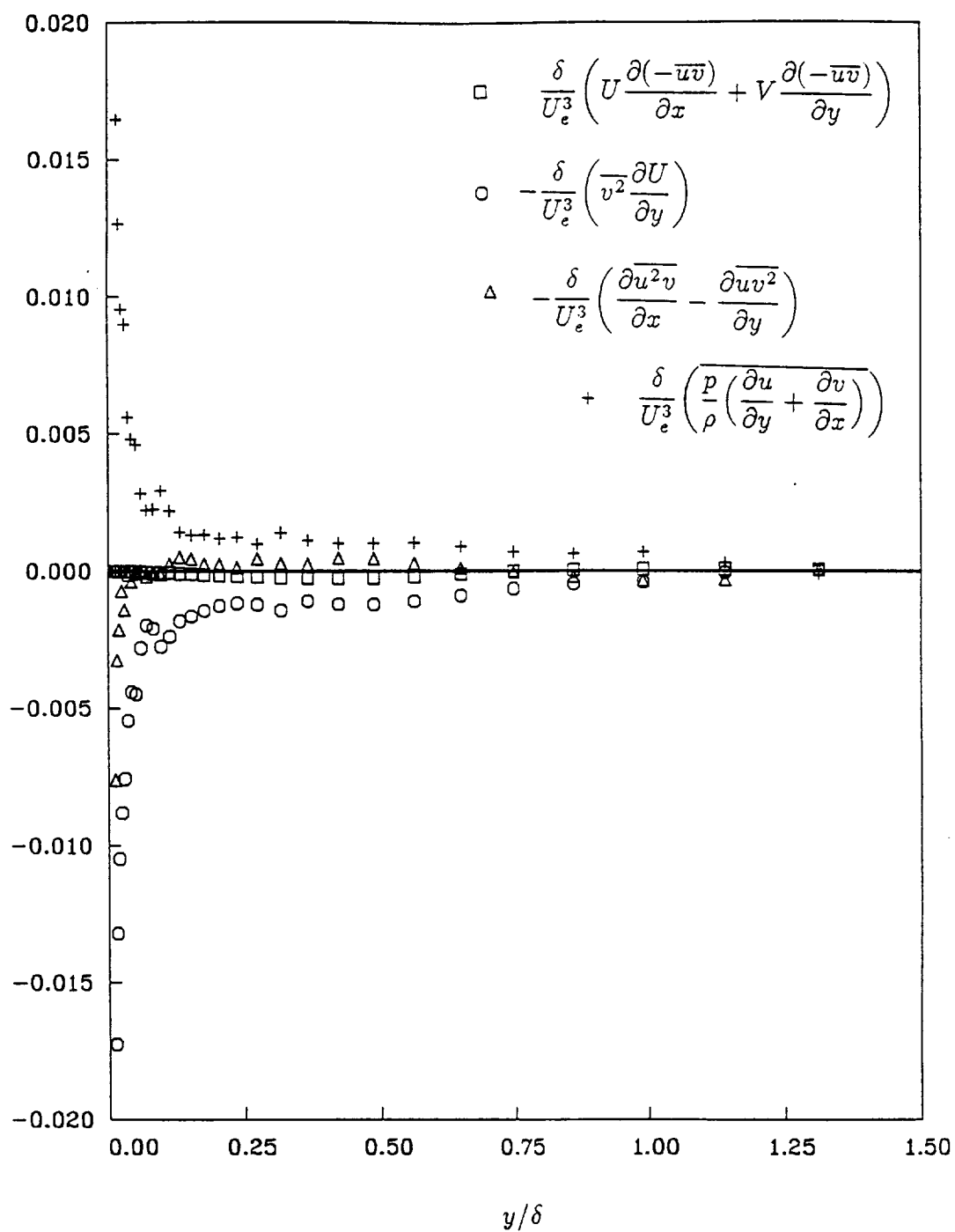












$\square$	$x/h = -1.05$	$\diamond$	$x/h = 15.13$
$\circ$	$x/h = 9.21$	$\nabla$	$x/h = 20.29$
$\triangle$	$x/h = 9.87$	$\boxtimes$	$x/h = 28.76$
$+$	$x/h = 10.53$	$\times$	$x/h = 38.55$
$\times$	$x/h = 11.84$	$\blacklozenge$	$x/h = 51.18$
	$x/h = 13.16$		

